



Compression of picosecond pulses from a thin-disk laser to 30fs at 4W average power

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Abstract: We investigate two approaches for the spectral broadening and compression of 1-ps long pulses of a thin-disk laser amplifier running at 50 kHz repetition rate at 1030 nm wavelength. We find that with a single, 2.66-m long stretched flexible hollow fiber filled with xenon gas, Fourier transform limited output pulse duration of 66 fs can be directly reached. For larger pulse shortening, we applied a hybrid cascaded approach involving a BBO-based pre-compressor and a long hollow fiber. We could achieve 33-times temporal shortening of 1-ps pulses down to a duration of 30 fs at an overall efficiency of ~29% with an output power level of 3.7 W. These results demonstrate the potential of stretched flexible fibers with their free length scalability for shortening laser pulses of moderate peak power.

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OCIS codes: (320.7160) Ultrafast technology; (320.7110) Ultrafast nonlinear optics; (320.5520) Pulse compression.

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1. Introduction

There is a growing demand for high-average-power, high-repetition-rate, sub-30 fs laser sources for a broad range of applications, e.g. terahertz technology, coincidence analysis in attosecond pump-probe measurements or ultrashort electron pulse generation. The laser systems for such applications are increasingly based on ytterbium-doped solid-state materials, which can be very efficiently pumped by high-power laser diodes and have low heat generation thanks to their small quantum defect. In order to achieve high average power levels, the thermal management of the active material plays a central role. Therefore, mainly three geometries have been established in this segment, which provide especially efficient cooling: thin-disk [1, 2], slab [3, 4] and fiber [5]. Although very recently direct diode-pumping has become available also for broadband Ti:Sapphire systems, due to some obstacles such as large quantum defect and sub-optimally matched pump diodes, this technology still needs to evolve [6]. Besides the many advantageous properties of ytterbium-based gain media, they exhibit on the down side a somewhat narrow bandwidth, which prohibits the direct generation of sub-30 fs pulses. Therefore, in order to reach this regime, additional pulse broadening and compression techniques need to be applied [7].

Currently, great effort is therefore being invested in the compression of few-100 μJ fiber laser pulses at high average power levels by conventional 1-m long hollow-core fibers (HCF) [8–11]. For example, sub-300 fs pulses could be shortened to the duration of sub-two optical cycles at 216 W average power by using a cascaded HCF arrangement [12, 13]. Great results with cascaded arrangements were also achieved at lower pulse energies (μJ) by using photonic crystal fiber compressors [14].

For gas-filled fibers, the recent introduction of stretched flexible hollow fibers (SF-HCF) opened up new opportunities because the length of nonlinear interaction is now freely scalable [15]. This concept allows spectral broadening by up to 20–30 times, well beyond the possibilities of traditional rigid HCFs [16]. The SF-HCF technology therefore promises an

appealing opportunity for directly compressing the ps, sub-ps pulses of diode-pumped solid-state (DPSS) or fiber lasers to sub-30 fs duration. We need such pulses for the efficient generation of THz radiation by optical rectification or via a non-collinear optical parametric amplifier [17], in order to compress electron pulses in time [18] for sub-cycle waveform electron microscopy [19] or for driving atomic-scale electron dynamics in condensed matter [20]. For these purposes 30 fs pulse duration is optimal in order to achieve high signal-to-noise ratio but no sample damage.

In this work we investigate how far this concept is applicable to normal laboratory-scale lasers with moderate average power levels. We introduce a new approach of cascading spectral broadening due to cascaded second-order nonlinearity in a BBO crystal and in a long SF-HCF. In this way we generate for the first time 30 fs pulses directly from picosecond pulses of a Yb:YAG thin-disk amplifier. We achieve ~4 W power level at 30 fs pulse duration and at a useful, intermediate repetition rate of 50 kHz. Beyond that such pulses are attractive for applications, the results also reveal the further perspective of our approach.

2. Single-stage spectral broadening

A thin-disk Yb:YAG amplifier [21] delivers linearly polarized, slightly positively chirped 1-ps pulses centered at 1030 nm wavelength with an average power of 15 W at a repetition rate of 50 kHz. The somewhat unfavorable combination of rather long output pulse duration together with the pulse energy of only 300 μ J in this particular laser system, which suffered from reduced power due to Pockels cell crystal degradation, makes large spectral broadening challenging, because the peak power of 0.28 GW is rather low for HCFs.

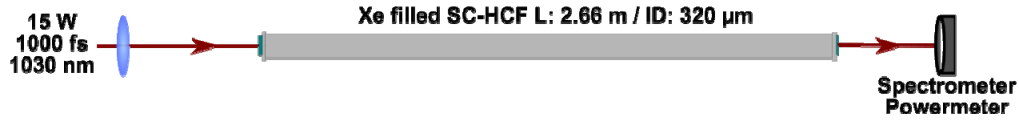


Fig. 1. Hollow fiber compressor. ID denotes inner diameter.

As depicted in Fig. 1, the pulses are focused by a lens into a 2.66 m long SF-HCF with an inner diameter (ID) of 320 μ m to undergo self-phase modulation. The length of the waveguide was limited by the available laboratory space, while the ID was a trade-off between waveguide transmission and achievable spectral broadening. The SF-HCF is filled with xenon at variable static pressures up to 10 bar to achieve sufficient spectral broadening during propagation. In order to estimate the performance of the experimental approach, the spectrally broadened pulses are recorded by a spectrometer as well as a power meter in order to evaluate the extent of spectral broadening and at the same time the efficiency, which are the two key parameters for applications.

Three experimental spectra, recorded at 3, 4 and 5 bar of xenon, are shown in Fig. 2(a). A regular spectral broadening due to self-phase modulation (SPM) is observed. The spectral width increases with the accumulated nonlinear phase, that is, the B-integral which is proportional to the applied pressure:

$$B = \frac{2\pi}{\lambda_0} \int_0^L p \kappa_2 I(z) dz, \quad (1)$$

where p is the gas pressure, κ_2 is the nonlinear refractive index of 1-bar gas having a unit of $\text{cm}^2/(\text{W} \cdot \text{bar})$, $I(z)$ is the peak intensity along the propagation and L denotes the length of the nonlinear interaction.

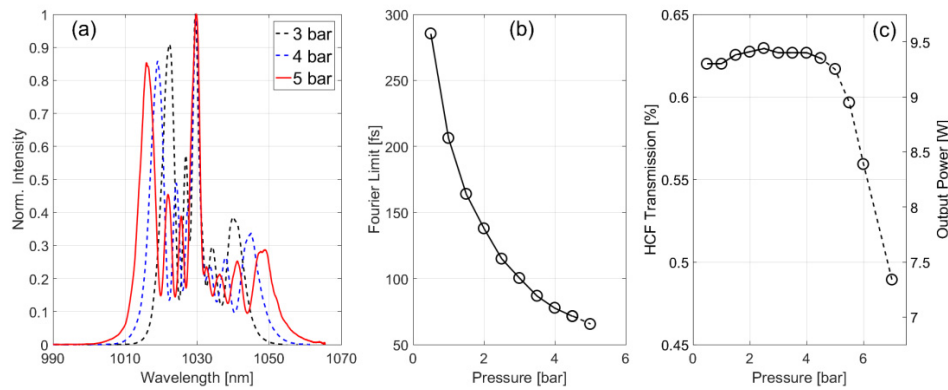


Fig. 2. Experimental results of the SF-HCF stage. (a) Typical spectra recorded after propagation through a 2.66-m long SF-HCF filled with 3, 4 and 5 bar of xenon (black, blue, red, respectively). (b) Transform-limited pulse duration in dependence of the pressure. (c) Pressure-dependent transmission through the SF-HCF. A sharp decline of the transmission can be observed around 4.5 bar and above.

The evolution of the corresponding Fourier-limited full-width at half maximum (FWHM) pulse duration is presented in Fig. 2(b). Increasing the xenon pressure inside the SF-HCF results in an increased B-integral, hence stronger self-phase modulation. The output spectrum supported a Fourier transform limited pulse duration as short as 65.6 fs at a pressure of 5 bar, which means a compression factor of ~ 15 at a B-integral of 22.5. At this condition the maximum achievable peak power corresponds to 2.4 GW. A further increase of the pressure in the SF-HCF setup did not prove to be beneficial, because the transmission of the SF-HCF started dropping (as shown in Fig. 2(c)), and the output pulse energy became fluctuating. At the same time a series of weak distinct spectral features appeared on both sides of the spectrum. These fluctuations amount to roughly 10% rms, which exceeds the 1.5% rms level, which our application can tolerate. At 5 bar gas pressure, the transmission is 62% and the peak power (assuming compressed pulses) increased by a factor of ~ 9.4 . Nevertheless, our target pulse duration of ~ 30 fs, which is essential for our purpose of generating multi-THz radiation by optical rectification, could not be reached.

In order to put our findings into context, Table 1 shows the performances of state-of-the-art single-stage HCF compressors applied to Yb-laser pulses at 1030 nm.

Table 1. Performance comparison for single HCF stage

	Pulse duration [fs]		Compression factor	HCF Transmission
	Input	Output ^a		
Current work	1000	66	15.2	62%
Rothhardt et al. [8]	700	66	10.6	52%
Hädrich et al. [9]	340	26 ^b	13.1	$\sim 54\%$
Lavenu et al. [10]	130	12.6	10.3	53%
Didenko et al. [11]	260	17 ^c	15.3	51%

^a Fourier transform limit of the output spectrum; ^b retrieved from simulations or ^c from autocorrelation measurements

Here, we compare the performances of the HCF itself in the various setups, therefore either the Fourier transform limit of the output spectrum or if it is not available the pulse duration derived from simulations or from autocorrelation measurements are given. The transmission values accounts for only the waveguides without the chirp management setups.

In most of previous research Yb:Glass systems were utilized as a seed source prior to spectral broadening, resulting in ~ 300 fs long initial pulses. Our results appear to be the first report on efficient pulse compression in a HCF starting from picosecond pulse duration. Due to the advantageous geometry of our SF-HCF [16] we achieved one of the highest compression factors so far at the highest transmission level among the measurements. The performance of single-stage HCF setups will be analyzed further theoretically in the upcoming section.

3. Simulations

In order to find out the most promising way to go down to 30 fs duration, we simulated the propagation along the HCF by applying a symmetrized split-step propagation code which solves the nonlinear Schrödinger equation taking self-phase modulation, self-steepening, linear losses and full dispersion of the gas-filled hollow waveguide into account. In the calculations, transform-limited input pulses of 1 ps, 500 fs and 250 fs duration were assumed. The spectrum at the output of the fiber was simulated for each input pulse at various gas pressures up to the critical pressure of self-focusing, in order to find the optimum. Figure 3(a) depicts the results, namely the transform-limited pulse durations obtained in the simulations. In Fig. 3(b) the same data is replotted as a function of the B-integral, which is more directly related to the general physics of the spectral broadening. According to Eq. (1), one can scale the B-integral either by changing the pressure or applying a longer waveguide.

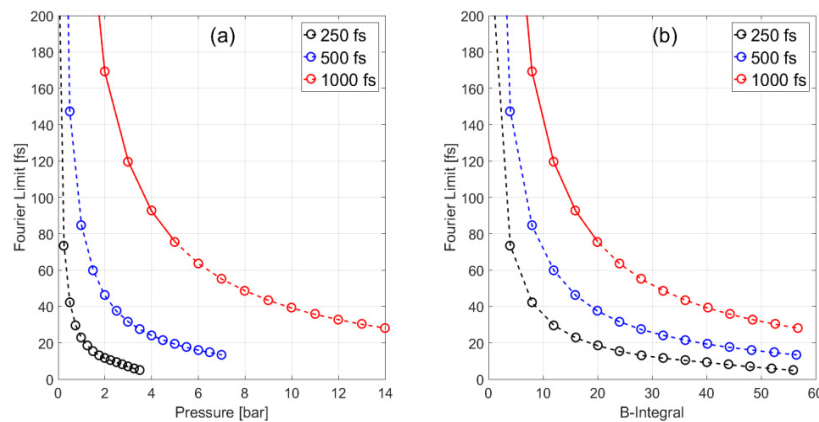


Fig. 3. Numerical simulations. (a) Transform-limited pulse duration after propagating 0.2-mJ pulses of different durations centered at 1030-nm wavelength through a 2.66-m long HCF at various xenon pressures. (b) Same data in dependence of the B-Integral.

The red curve in Figs. 3(a) and 3(b) corresponds to the experimental case, where the solid line marks the regime of stable operation. Theoretically, one would expect to reach a B-integral of up to 55 before self-focusing sets on. This value would correspond to ~ 30 -fs transform limited pulses. However, in the experiment, we only achieved a maximum B-integral of ~ 23 without creating imperfect operation conditions. Nevertheless, the corresponding spectrum had 8 peaks, which is comparable to the largest spectral broadening achieved to date by a hollow-core fiber arrangement [16]. The blue and black circles in Fig. 3(a) and (b) suggest that starting with slightly shorter pulses can substantially help with generating shorter pulses. This prediction is tested experimentally in the next section.

4. Hybrid double-stage spectral broadening

According to the simulations of Fig. 3(a) we need to feed roughly 400-fs pulses into the SF-HCF compressor in order to reach the 30-fs regime. A straightforward way would be to use two cascaded HCFs [22] with an intermediate pulse compressor, which can dramatically improve the achievable spectral broadening, but on the other hand increases the footprint and

complexity of the setup. For our proof-of-principle experiment we chose a novel approach: a hybrid two-stage arrangement, where the first stage is based on cascaded second-order nonlinearity in a beta-barium borate crystal (BBO) [23, 24], not the least to obtain practical experience with this approach.

In order to characterize the performance of the BBO-based spectral broadening stage, we recorded the spectrum and its transform-limited pulse duration, which was calculated for three different thicknesses of the BBO crystal, while gradually increasing the pump intensity. Figure 4 summarizes the results. As expected, higher intensities result in more spectral broadening and shorter Fourier limits.

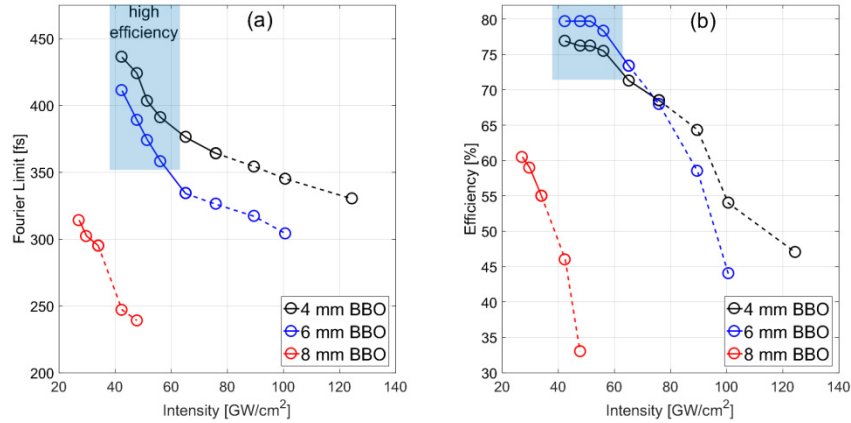


Fig. 4. Performance of the BBO-based spectral broadening stage. (a) Fourier limit dependent on the crystal thickness. (b) Conversion efficiency as a function of pump intensity.

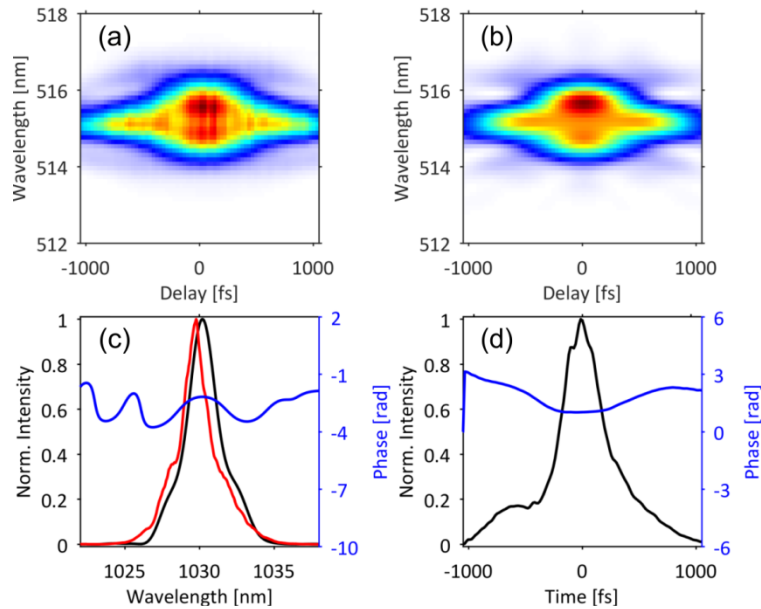


Fig. 5. Measured pulse shape after the first compression stage. (a) Measured and (b) retrieved FROG traces. (0.82% FROG error on a 512x512 grid) (c) Evaluated spectrum and spectral phase. (d) Retrieved pulse shape with temporal phase. The pulse duration is 409 fs.

The entirely stable operation regime is again indicated by solid lines. The thicker the applied crystal, the lower was the achievable pulse duration, but also the efficiency. The lower efficiency of thicker crystals is due to the larger conversion efficiency to second harmonic, which acts as a loss for our purposes and is filtered out. We find a sweet point by using a 6 mm crystal at 50-55 GW/cm², which produced the required pulse duration at conveniently high efficiency of 75-80% and stable operation.

The spectrally broadened pulses from the BBO stage optimized for 15 W input power (0.3 mJ) were compressed by a grating pair (1000 lines/mm) and subsequently characterized by a second-harmonic-generation frequency-resolved optical-gating setup (SHG-FROG), incorporating an 80- μ m thick BBO crystal for SHG generation and a wavelength-calibrated spectrometer. Figure 5 shows the results, indicating 409-fs pulses after the BBO stage.

Finally, the compressed pulses at 10 W average power level (0.2 mJ) from the BBO stage were launched into the 2.66-m long SF-HCF of 320- μ m inner diameter filled with xenon gas. The output spectrum was measured by a sensitivity-calibrated spectrometer (NIR512, Ocean Optics). Figure 6(a) shows three typical spectra recorded at 2, 3 and 4 bar pressure, respectively. Figure 6(b) and (c) show the corresponding Fourier-limited pulse durations (FWHM) and the efficiency of the SF-HCF in dependence of the pressure.

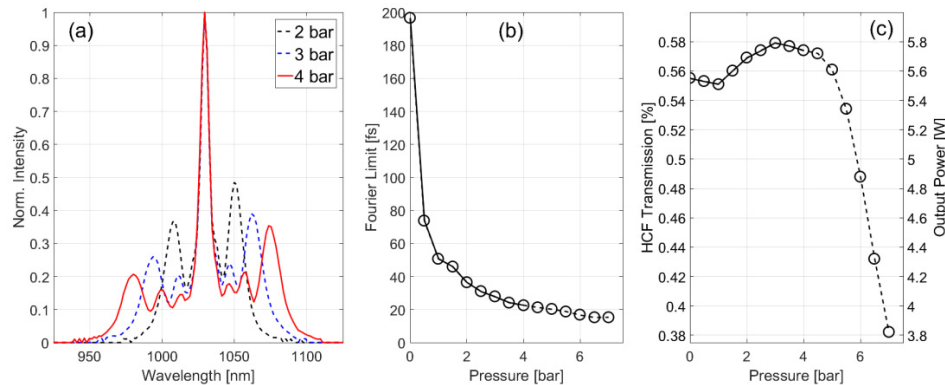


Fig. 6. Pulse characteristics after cascaded pulse shortening in BBO and SF-HCF. (a) Typical output spectra for 2, 3 and 4 bar of xenon. (b) Fourier-limited pulse durations in dependence of the pressure, breaking into the sub-30 fs. (c) Pressure-dependent transmission through the SF-HCF. Solid lines between the data points indicate the regime of stable operation.

At 4-bar pressure the transform-limited pulse duration is 22.5 fs at stable operation over the full day. The corresponding peak power reaches 4.4 GW, which is a factor of ~ 1.8 times higher than in the single HCF stage. We compressed the output of the hybrid arrangement by a set of chirped mirrors (PC1611, Ultrafast Innovations GmbH) and characterized the final pulse shape by using the same SHG-FROG setup as described above. The full experimental arrangement is shown in Fig. 7.

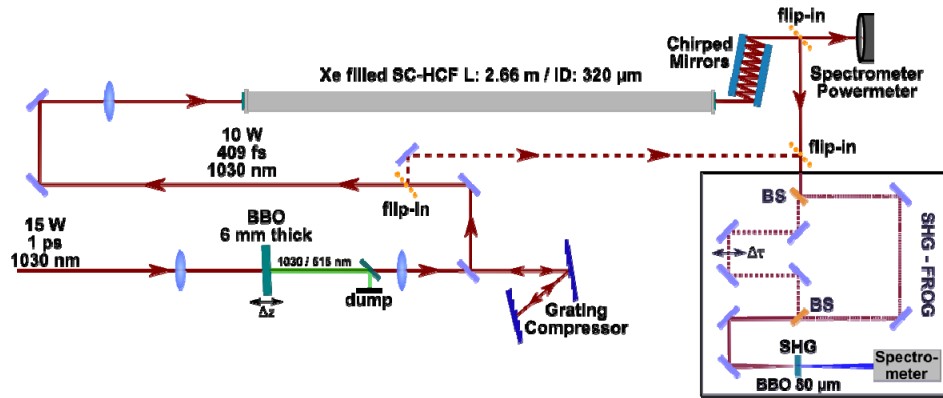


Fig. 7. Experimental setup utilizing cascaded spectral broadening in BBO and a SF-HCF for two-stage compression of 1-ps pulses down to 30-fs duration. BS denotes beam splitter, $\Delta\tau$ time delay.

Figure 8 shows a FROG measurement of the pulses compressed by the cascaded arrangement.

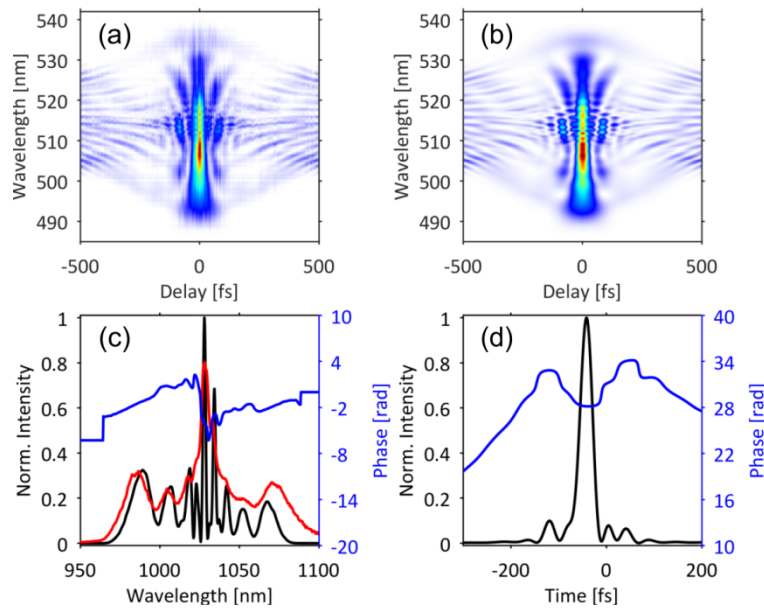


Fig. 8. SHG-FROG measurement of the output pulses after compression by the two-stage arrangement. (a) Measured and (b) retrieved FROG traces. (0.43% FROG error on a 1024x1024 grid) (c) Evaluated spectrum and spectral phase. (d) Retrieved pulse shape with temporal phase. The pulse duration is 29.8 fs.

The displayed measurement was carried out at an input power level of 12.8 W before the BBO stage, resulting in 8.5 W at the entrance of the HCF and 3.7 W average power of the compressed pulses. This corresponds to 74 μ J pulse energy and 1.5 GW peak power, which was determined by dividing the measured pulse energy by the integral of the retrieved pulse shape on ± 1.5 ps time window. The obtained pulses are well suited for further non-linear optical conversions or direct applications. The SF-HCF was filled with 4 bar of xenon.

The FROG data reveals a 29.8-fs pulse duration very close to the transform limit of the retrieved spectrum (27.1 fs). The main peak contains 67% of the full pulse energy. We note, that the retrieved spectrum reveals a fast oscillation around the carrier wavelength of 1030

nm, which is the result of the interference of low-level pedestals of the compressed pulse after the BBO stage. This modulation has been resolved by the FROG measurement due to its large measured delay range of 2049 fs, but could not be resolved by our spectrometers (see the single peak at 1030 nm of the reference spectrum in Fig. 8(c) and also in Fig. 6(a)). The cascaded scheme's overall compression factor is >30 in terms of pulse duration, as shown in Table 2. Interestingly, if considering the physics of the second stage alone, we achieved a compression factor of 13.6 in the hollow fiber, similar to the uncompressed case shown in Sect. 2. The SF-HCF's efficiency was only slightly lower than in the uncompressed case, which is attributed to the slightly lower beam quality after the BBO stage.

As it is shown in Table 2 our novel approach utilizing a hybrid $\chi^{(2)}$ – SF-HCF setup, shows a comparable performance to former cascaded pulse shortening results for Yb-based sources at a much reduced complexity. Again, our experiments appear to be the first reports of cascaded shortening starting with picosecond pulse durations.

Table 2. Performance comparison for cascaded compressor setups

	Method	Pulse duration [fs]		Compression factor	Overall transmission
		Input	Output		
Current work	$\chi^{(2)}$ / SF-HCF	1000	29.8	33.5	29%
Rothhardt et al. [12]	HCF / HCF	210	7.8	26.9	35%
Hädrich et al. [13]	HCF / HCF	240	6.3	38.1	53%
Mak et al. [14]	PCF / PCF	250	9.1	27.5	36%

5. Conclusions

In conclusion, we investigated two approaches for the compression of 1 ps long pulses of a thin-disk amplifier running at 50 kHz repetition rate, centered at 1030 nm. We find that a single, 2.66-meter long stretched flexible hollow fiber setup can produce a substantial spectral broadening despite the unfavorably low peak power of the input pulses. It shows a good overall efficiency of 62% clearly over-performing the traditional rigid HCFs (see Table 1) but becomes unstable for xenon pressures above 5 bar. We introduced a hybrid cascaded approach involving a BBO-based pre-compressor and a long SF-HCF. With this novel arrangement we could achieve 33-times temporal shortening of 1 ps pulses down to a duration of 30 fs, which is very convenient for further experiments and applications. Although the cascaded scheme suffers from overall losses, it is capable of generating ultrashort pulses with ~ 1.8 -times higher peak power as compared to a single SF-HCF. For our purposes to generate 30 fs pulses, we find this solution as a good compromise, because the first BBO stage does not increase the complexity of handling and alignment requirements, like two-HCF setups would do. If even shorter pulses are required, one can sacrifice the simplicity and switch to SF-HCF / SF-HCF cascading having the potential for sub-2-cycle pulse compression.

The compressed 30-fs pulses have been successfully applied for the generation of THz radiation [25].

Funding

European Research Council; Munich-Centre for Advanced Photonics.

Acknowledgment

We thank Ferenc Krausz for general support.